

Radiation and Emission Characteristics of Laminar Partially-Premixed Flames of Petroleum Diesel-Canola Methyl Ester Blends

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Abstract

The primary objective of this study was to compare the effects of fuel-chemistry on the combustion properties of blends of Canola Methyl Ester (CME) and petroleum-based No.2 diesel in premixed flames at different initial equivalence ratios (1.2-7.0) in the fuel-rich regime. The fuel was vaporized and injected into a hot air stream and burned as a laminar flame at atmospheric pressure. The equivalence ratio was altered by changing the air flow rate. The flame appearance, global CO and NO emissions, and flame radiation were documented. The measured radiative heat fraction significantly increased with equivalence ratio. A decrease in the measured radiative heat fraction was observed as the volume percentage of CME was increased in the blend. The CME flames produced the highest emission index of NO, which declined as the volume percentage of CME was decreased in the fuel blend. In contrast, the diesel flame produced the highest emission index of CO, which decreased as the volume percentage of CME was increased in the blend.

Keywords

Diesel; Canola Methyl Ester; Combustion

Introduction

The increasing demand of petroleum fuels has resulted in a fast depletion of the natural petroleum resources and has sparked interest in the development of alternative fuels. Currently, 86 million barrels of oil are consumed world-wide per day; which is expected to increase to 121 million barrels a day by 2025, according to Pahl (2008). In 2009, petroleum accounted for 94 percent of the total use of energy in the transportation sector and was predicted to increase (US Department of Energy, 2010). The recent escalation of petroleum oil price has further prompted interest in fuel substitutes. Biofuels, such as canola methyl ester (CME), are viable alternatives to petroleum fuels, particularly for transportation, whose

sources are renewable, locally grown, and free of sulfur and carbon-neutral. CME is produced by the transesterification of canola oil. Blends of CME and diesel can be readily used in current automobiles with minimal modifications. The use of such biofuels currently accounts for less than 1% of the total fuel consumption in the USA and Europe; in addition to cost considerations, the lack of detailed knowledge of the combustion behavior of biofuel blends is an inhibitor in the widespread use of these fuels.

In the last several decades, heavy-duty diesel engines have been regulated for smoke opacity, nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). Current standards specify emission limits for nonmethane hydrocarbons (NMHC) as well. The U.S. Environmental Protection Agency (EPA), in its national emissions inventory, estimated that diesel vehicles were responsible for 60% of on-road emissions of PM and 45% of on-road in 2000 (EPA report, 2003).

Several researchers have reported studies on exhaust emissions of diesel engines when operated using neat transesterified biofuels and their blends with diesel fuel. The results included a reduction in CO, smoke and PM, along with an increase in the oxides of nitrogen. Also, an increase in fuel consumption was observed due to the slightly lower energy content of biofuels compared to petroleum fuels. A number of fuel properties (viscosity, heating value, density and cetane number), as well as engine operating conditions have been shown to affect emissions from engines using biofuels.

Schumacher et al. (2001) compared the performance of two Detroit Diesel Corporation Series 60 engines that were fueled with various blends of biofuel and petroleum diesel fuel. The results of this study were in

agreement with those from previous studies on two and four stroke diesel engines; and an increase in NO_x emissions, accompanied by a decrease in CO, particulate matter, and unburned hydrocarbons was observed. Canakci and Gerpen (2003) used petroleum diesel, yellow grease biofuel and soybean oil biofuel in a four-cylinder turbocharged diesel engine, at steady-state engine operating conditions. The use of both biofuels resulted in significant reductions in PM, CO, and unburned hydrocarbons. One of the studies (Labeckas and Salvinskas, 2006) showed the effects of rapeseed methyl ester (RME) on the exhaust emissions with a four-stroke, four-cylinder diesel engine. The engine was operated on neat RME and its 5%, 10%, 20% and 35% blends with diesel fuel. An increase in NO_x emissions was observed with increasing engine speed; and the result was attributed to the increased mass percentage of oxygen in the biofuel.

Tsai et al. (2010) investigated the emissions of PM, total carbon (TC), e.g., organic/elemental carbons, and polycyclic aromatic hydrocarbons (PAHs) from a diesel generator fuelled with soy-biodiesel blends. Among the tested diesel blends (B0, B10 (10 vol% soy-biodiesel), B20, and B50), B20 exhibited the lowest PM emission concentration despite the loads (except the 5 kW case), whereas B10 displayed lower PM emission factors when operated at 0 and 10kW than other fuel blends. Fontaras et al. (2010) tested five biodiesels from different feedstocks (rapeseed, soy, sunflower, palm, and used fried oils) blended with diesel (10% by volume) on a Euro 3 common-rail passenger car and found that NO_x emissions increased by up to 20% for two out of the five blends, decreased by up to 15% for two other blends, and remained unchanged for one blend; besides, PM was reduced for all blends by up to 25% and the reductions were positively correlated with the extent of biodiesel saturation. In general, pollutant emission studies in engines have shown that the majority of biofuels produced more NO_x, less CO, PM, and unburned hydrocarbons than diesel fuel.

The aforementioned effects observed in engines are too complex to analyze, due to the interactions of engine design, operating conditions, and fluid-mechanics. To develop remedial steps, it is essential to separate the effects of fuel chemistry from those of engine variables. A flame technique has been developed by Love et al. (2009a) to isolate the effects of fuel chemistry on the combustion properties of biofuels. The partially-premixed laminar flames of prevaporized pure biofuels have been studied using

this technique (Love et al., 2009b). The measured flame temperature and the soot volume fraction reported in these studies agreed well with those obtained from engine studies. Thus, the laminar flame arrangement provides a convenient venue to study the effects of only fuel composition and chemistry on the combustion properties.

The primary objective of this study was to compare the combustion characteristics of blends of CME, and petroleum-based No.2 diesel at varying equivalence ratios (Φ) of 1.2, 2, 3 and 7. The equivalence ratio is the ratio of the fuel-to-air mass ratio to the stoichiometric fuel-air mass ratio (Turns, 2000). Equivalence ratios greater than one signify rich fuel-air mixtures. These equivalence ratios were chosen to simulate the partially-premixed to non-premixed combustion zones that exist in the vicinity of the burning spray in diesel engines (not the overall equivalence ratio). The documented combustion characteristics include the flame appearance, the global emissions, and the total radiative fraction of heat release. The advantage of this method is that it provides a quick comparison of the major combustion properties (sooting tendencies and pollutant emissions) of various fuels, while utilizing small quantities of the fuel.

Experimental Set-Up and Methods

A description of the experimental set-up, instrumentation, fuels and test conditions is provided in this section.

Experimental Set-up

The experiments were conducted in a vertical steel test chamber with a cross section of 76x76 cm and height of 100 cm. The top of the combustion chamber was connected to the atmosphere through an exhaust duct. The ambient pressure in the laboratory was maintained slightly (20 Pa) above the atmospheric pressure, to provide a positive draft inside the test chamber and eliminate leakage of the combustion products into the main laboratory facility. High temperature heating tape with a proportional temperature controller was used to heat the flow lines carrying air to the desired temperature of 400°C (which was close to the final boiling point of the liquid fuels) to completely vaporize the liquid fuels, without any coking. The liquid fuel was injected with a variable speed syringe pump and a 50 cm³ capacity syringe into the heated air (carrier gas) stream through

a high temperature silica-based septum. The vaporized fuel/air mixture was sent to a 9.5 mm inner diameter tube burner. The volumetric flow rate of the carrier gas was monitored using a calibrated rotameter. The feed line temperature was monitored using K-Type thermocouples. A schematic diagram of the experimental set-up is presented in Fig. 1. The vaporized fuel was ignited using a pilot flame, which was removed after ignition. The resulting flame was laminar (the burner exit Reynolds number was maintained below 120), whose characteristics were dependent on the chemistry of the fuel alone. The burner exit equivalence ratio was altered by changing the flow rate of air, while the fuel flow rate and thus energy input rate were constant.

Fuels

Three blends of CME with petroleum-based diesel were used: B25, B50 and B75 with 25%, 50% and 75% volume concentration of CME. The blends were prepared using a splash blending technique (Reid, 2007) in 5 US gallon (20 liter) amounts. In addition, pure CME and diesel were used to provide a baseline for comparison. The molecular formula, chemical composition and physical properties of No. 2 diesel fuel and canola methyl ester as well as the blends are presented in Table 1. A decrease in the heating value and an increase in the oxygen content are observed as the volume percentage of CME is increased in the blend. The large amount of air flow and length of the heated tube ensured that the vapors of the fuel components were well-mixed at the exit of the burner in spite of any preferential vaporization of the blend components.

Flame Visualization

Visible flame images were acquired using an 8 mega pixel digital AF SLR camera (EOS Digital Rebel XT/EOS 350D). The images were obtained under similar lighting conditions with a dark background at 1/25 second shutter speed. Using appropriate software, the number of pixels was counted and converted into length using a calibration reference.

Radiation Measurement

A wide view-angle (150°) high sensitivity pyrhelimeter was used to measure the radiation from the flame. The pyrhelimeter was located far enough (50 cm) from the burner, so that its view-angle covered the entire flame length and the flame could be assumed as a point source. The pyrhelimeter had a

linear output with a sensitivity of 23.65 W/m²/mV. A data acquisition board along with suitable software was used to sample the measured radiative heat flux. Each test was run for 3 min with a sampling rate of 1 Hz, allowing the heat flux to reach a steady value. The background radiation was subtracted from the total radiation measured to give the flame radiation (q). The radiative heat fraction was then computed using equation (1):

$$F = (4\pi l^2 q) / (m \text{ LHV}) \quad (1)$$

Here, l is the distance between the flame and pyrhelimeter, m is the fuel mass flow rate and LHV is the lower heating value of the fuel. The radiative heat fraction characterizes the fraction of energy emitted from the flame in the form of radiation. Since most of the radiation in these flames is emitted by burning soot, the radiative heat fraction provides a convenient measure of the soot content in these flames.

Global Emissions

The emissions from the flame were measured by collecting gas samples through an uncooled quartz probe (1 mm diameter tip, expanding to a 6 mm ID tube) placed at the top of a pyrex flue gas collector. The pyrex flue gas collection funnel was placed 25 cm above the burner exit to collect the combustion products. Since the jet exit velocities were similar for all conditions, the entrainment and dilution was similar at this location for all fuels. Likewise, the temperature variation of the products was small. The flue gas collector and probe were aligned axially with the burner and the probe was placed above the flame. The gas samples were passed through a filter and ice-chilled water bath to remove particulates or moisture that might be present in the sample gas. A portable flue gas analyzer was used to measure the concentration of nitric oxide (NO), carbon dioxide (CO₂) and carbon monoxide (CO). The analyzer was calibrated with standard zero and reference gases before measurements were taken. The global emissions measurements were corrected to account for dilution of the product gases due to entrainment from ambient air. Therefore, the emission index (Turns, 2000) was used to characterize the pollutant emissions. The emission index expresses the amount of pollutant formed per unit mass of the fuel burnt:

$$EI_i = [X_i / (X_{CO} + X_{CO_2})] [(N \text{ MW}_i) / \text{MW}_f] \quad (2)$$

Here X_i represents the mole fraction of species i , N is the number of carbon atoms in the fuel, and MW_i MW_f

are the molecular weight of species i and fuel respectively. It is assumed that all the carbon in the

fuel is converted into CO or CO₂; which is reasonable because the soot content in the flames is small.

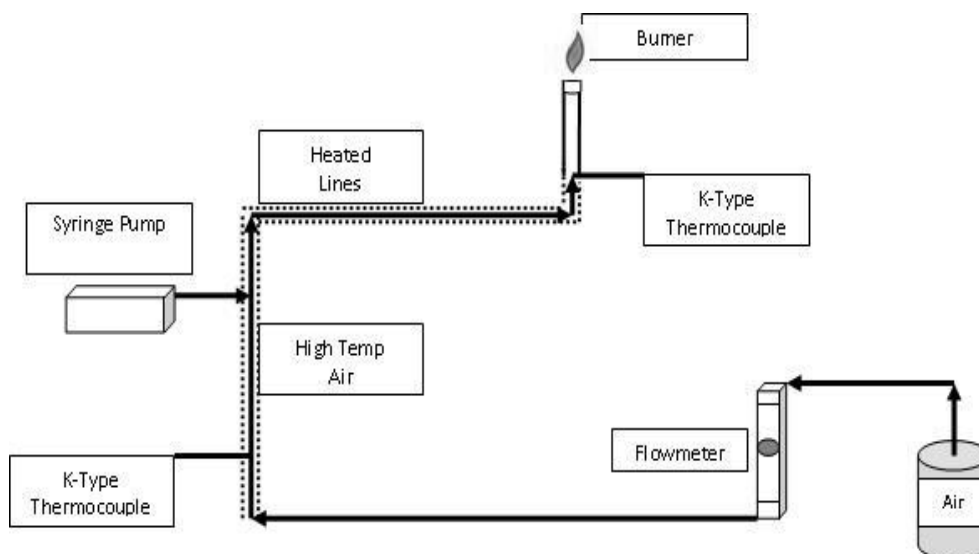


FIG. 1 SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SET-UP

TABLE 1. FUEL PROPERTIES

| Properties | Molecular Formula | Molecular Weight | Density (kg/m ³) | LHV (MJ/kg) | Oxygen (Mass %) |
|------------|---------------------------------------------------------|------------------|------------------------------|-------------|-----------------|
| Diesel | C _{14.4} H _{24.9} | 197.7 | 843 | 42.6 | 0 |
| CME B25 | C _{15.27} H ₂₇ O _{0.38} | 215.88 | 846 | 41.3 | 2.81 |
| CME B50 | C _{16.28} H _{29.45} O _{0.82} | 237.97 | 853 | 40.0 | 5.51 |
| CME B75 | C _{17.52} H _{32.42} O _{1.35} | 264.32 | 863 | 38.7 | 8.18 |
| CME | C ₁₉ H ₃₆ O ₂ | 296 | 876 | 37.4 | 10.81 |

Results and Discussion

Flame Appearance

The flames varied in color, structure, and length with change in equivalence ratio (Φ) that is the ratio of the stoichiometric air-fuel mass ratio to the actual air-fuel mass ratio. As the initial equivalence ratio was increased, less air was supplied, thus more air from the surroundings needed to be entrained, requiring an increase in length to effectively burn the fuel. A comparison of the flame images for CME B50 fuel at different equivalence ratios is provided in Fig. 2. As the equivalence ratio was increased from 1.2 to 7, the flame length increased from 4 to 20 cm. Also, the clear region near the injector became smaller. A visual comparison of the flames of various fuels at a constant equivalence ratio of 2 is presented in Fig. 3. It is observed that the flames of CME, diesel and the blends were similar in height and structure at the same equivalence ratio.

From the pictures, two primary regions were observed,

a clear region (which appeared blue in color pictures) close to the injector exit and a luminous bright region in the flame away from the injector. The length of the clear region decreased as the volume percentage of CME in the blend was reduced. The near-injector clear zone represents the primary gas-phase oxidation reaction zone. In this region, the fuel-bound oxygen, in case of CME and its blends (Table 1), was available to participate in the oxidation of carbon monoxide and nitrogen, thus resulting in the blue hue observed at the base of the flame (Kitamura et al., 2001). The remaining unburned carbon continued to burn downstream with ambient oxygen, emitting continuum radiation at all wavelengths, thus appearing luminous yellow. At the same equivalence ratio, the diesel flame was the most luminous, with the luminosity decreasing as the CME concentration in the fuel was increased, indicating the presence of less soot in the flame with an increase in the CME content.

Global Radiation

The measured radiative heat fraction, presented in Fig.

4, significantly increased with equivalence ratio due to the increased soot formation as the exit fuel/air ratio became rich. The uncertainties in the measurements are presented as error bars. For each equivalence ratio studied, the diesel flame produced the highest value of radiative heat fraction; and a decrease in the measured radiative heat fraction was observed as the volume percentage of CME was increased in the fuel blend. The presence of fuel-bound oxygen in the CME blends played a significant role in the reduction of soot formation in these flames (as observed in the decrease in flame luminosity and increase in the near-injector homogeneous reaction zone in Figs. 2 and 3).

Global Emissions

The measured NO emission index for the fuels tested at the four equivalence ratios is presented in Fig. 5. The results indicate that the NO emissions decreased as the equivalence ratio was increased from $\Phi = 1.2$ to $\Phi = 7$ for all the fuels. For each equivalence ratio used, the pure CME flame produced the highest emission index of NO, followed by the CME B75, CME B50, and CME B25 flames and the lowest NO emission index was documented for the diesel flame.

In contrast, the CO emission index increased, as the equivalence ratio was increased from $\Phi = 1.2$ to $\Phi = 7$ for all fuels tested (as seen in Fig. 6). The diesel flame produced the highest emission index of CO followed by the CME B25, CME B50, CME B75 and CME flames at all equivalence ratios. These observations are similar to those documented during engine testing, as discussed earlier.

A high level of correlation among radiation, soot, and luminosity can be seen in the results presented above. The flames of CME biofuel and its blends produced lower radiation and CO emissions, but higher NO emissions than the diesel flame. The effect of additional oxygen in the molecular structure of CME and its blends contributes to the lower CO emissions and radiative heat emission. The production of low amounts of soot leads to less heat radiated, and higher temperatures, and consequently more thermal NO formation (Turns, 2000). Detailed in-flame measurements of temperature, soot volume concentrations and in-flame CO and NO concentrations are necessary to further understand the combustion characteristics of these flames.

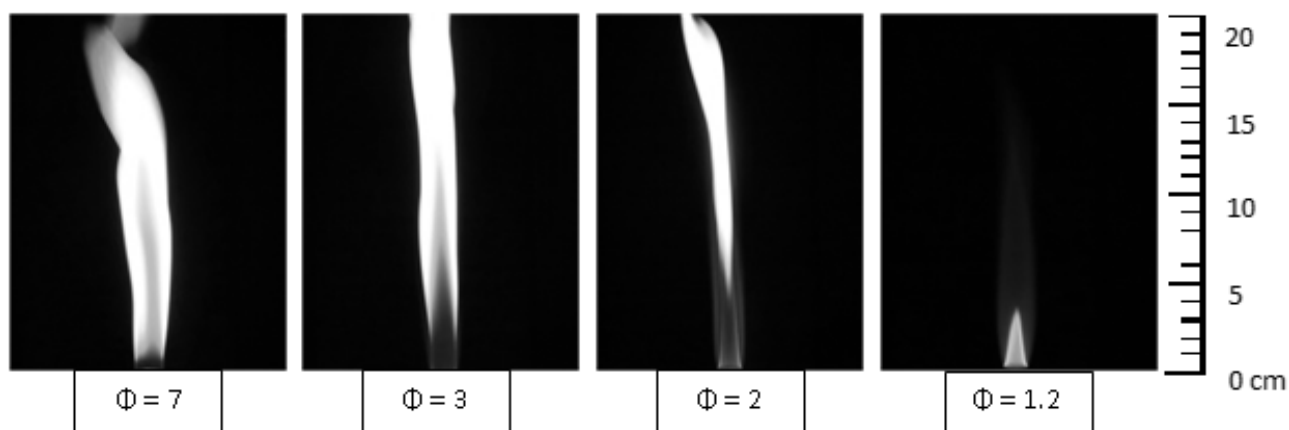


FIG.2. PHOTOGRAPHS OF CME B 50 FLAMES

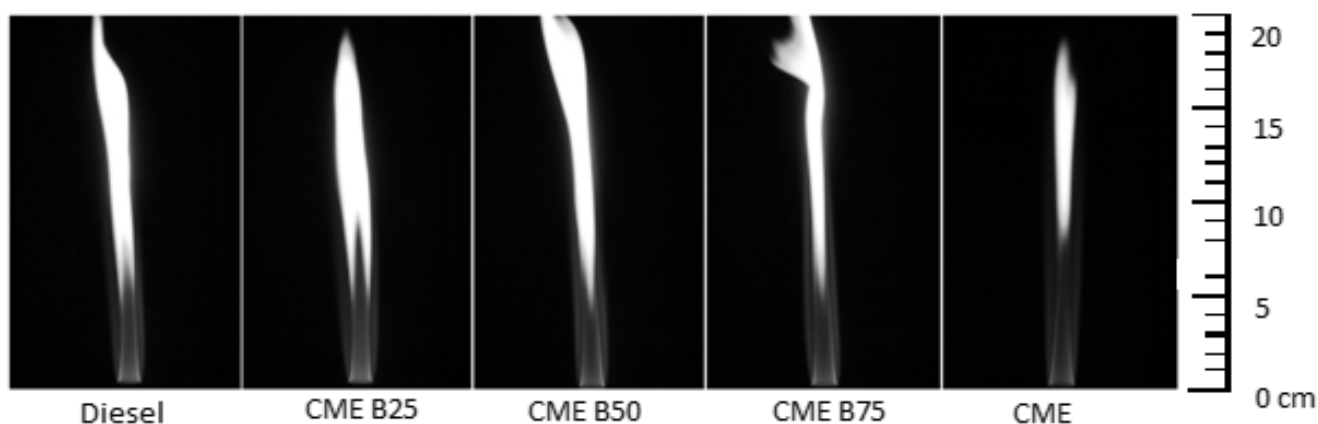


FIG.3. PHOTOGRAPHS OF FLAMES OF DIFFERENT FUELS AT AN EQUIVALENCE RATIO OF 2

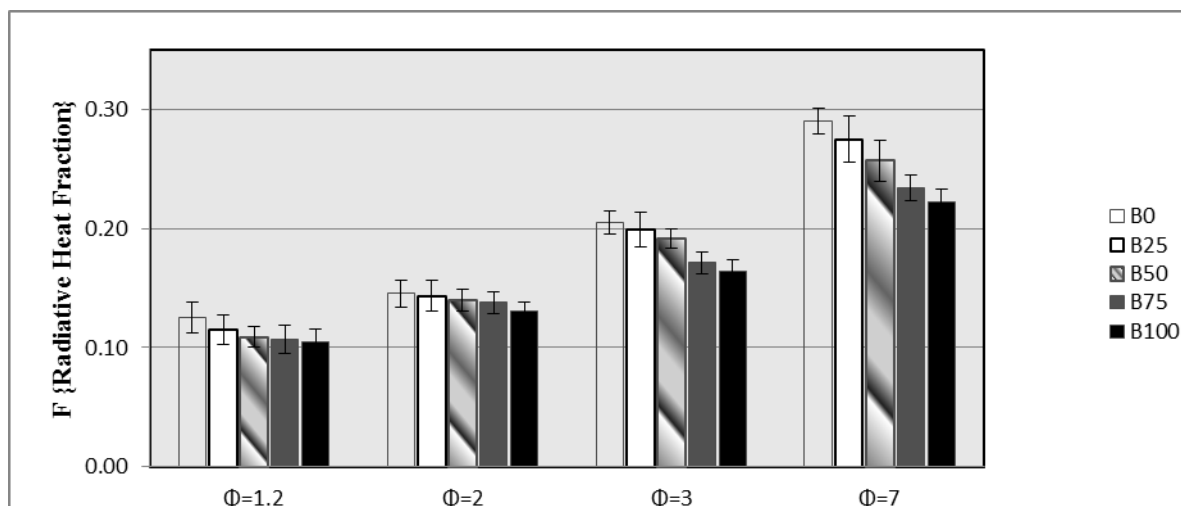


FIG.4. COMPARISON OF RADIATION FROM DIFFERENT FLAMES

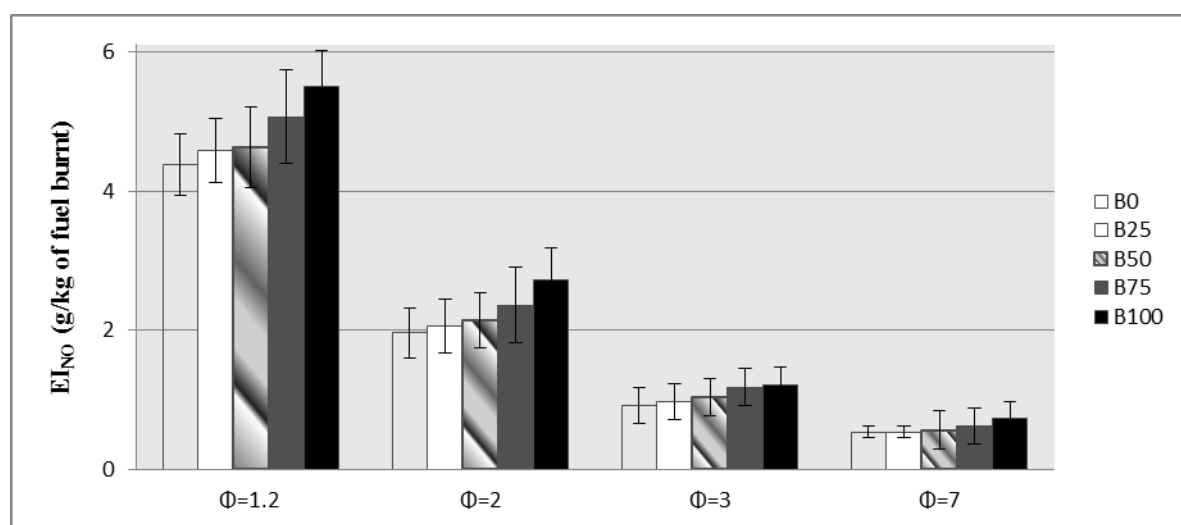


FIG.5. COMPARISON OF NO EMISSION INDEX OF DIFFERENT FLAMES

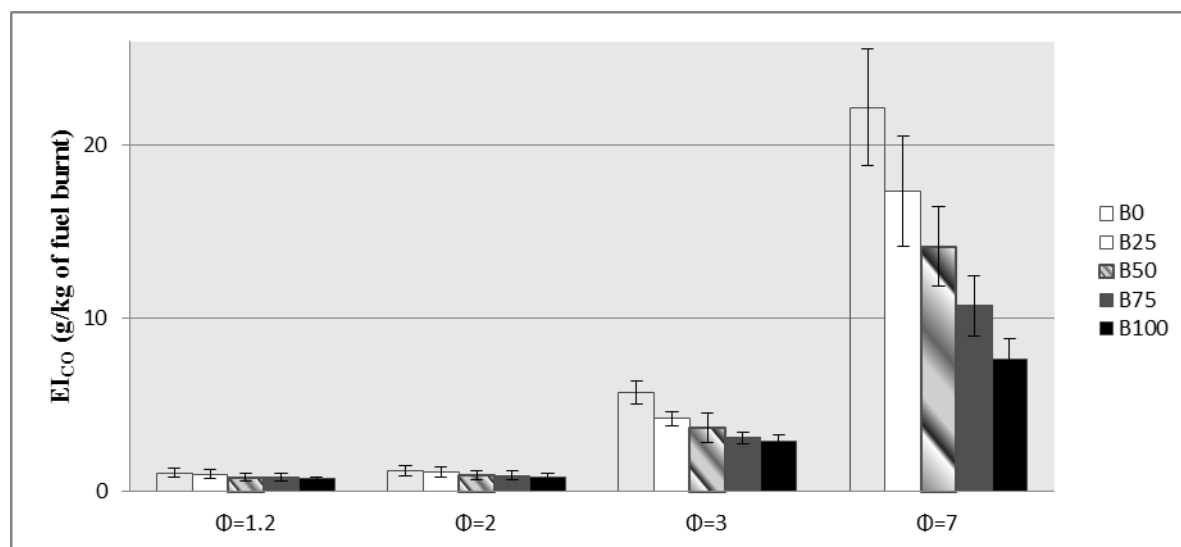


FIG.6. COMPARISON OF CO EMISSION INDEX OF DIFFERENT FLAMES

Conclusions

A method of rapid characterization of the soot/pollutant forming characteristics of fuels was

used to investigate the effects of exit equivalence ratio on radiation and emissions in flames of petroleum diesel-CME blends. The following conclusions were drawn:

(a) For all fuels tested, the flame length decreased and the color changed from yellow to blue as the equivalence ratio was decreased from 7 to 1.2, indicating complete combustion close to stoichiometric air-fuel ratio.

(b) The radiative heat fraction and the CO emission index significantly rose with increasing equivalence ratio showing increased tendency of the flames to produce soot at higher equivalence ratios due to incomplete combustion. A decrease in radiative heat fraction and the emission index of CO was observed as the volume percentage of CME was increased in the blend due to the presence of oxygen in the molecular structure of the CME biofuel.

(c) The NO emissions decreased and the CO emissions increased as the equivalence ratio was increased from 1.2 to 7 for all fuels tested. An increment in the emission index of NO and a decrement in the CO emission index were observed as the volume percentage of CME was increased in the blend. While the presence of the fuel-bound oxygen can be attributed to the reduction in CO emission index, more measurements are needed to reveal the reasons behind the increased NO emission with the CME content of the fuel.

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